COMPARISON OF SEISMIC TOMOGRAPHY, STRAIN RELIEF, AND ULTRASONIC VELOCITY MEASUREMENTS TO EVALUATE STRESS IN AN UNDERGROUND PILLAR

D. F. Scott
J. M. Girard
T. J. Williams
D. K. Denton

NIOSH
Spokane, WA

ABSTRACT

Personnel from the Spokane Research Laboratory, National Institute for Occupational Safety and Health, examined an underground pillar at the Homestake Mine, Lead, SD. Investigations involved strain relief and seismic tomography studies in the mine, and ultrasonic velocity measurements on pillar core in the laboratory. Measured octahedral normal stress was 37 MPa (5,366 psi); seismic P-wave velocities averaged 5.2 km/s (17,060 ft/s); and ultrasonic velocities at a pressure of 39.6 MPa (5,750 psi) averaged 6.3 km/s (20,669 ft/s). The difference between in-mine and laboratory velocities is attributed to the attenuation of seismic energy by mine fractures larger and more numerous than those in the samples of core measured in the laboratory. Using these results, researchers hypothesize that pillar rocks have the ability to withstand stress an order of magnitude greater than they currently sustain.

INTRODUCTION

Personnel from the Spokane Research Laboratory (SRL), National Institute for Occupational Safety and Health, conducted strain relief and seismic tomography studies on an underground rock pillar at the Homestake Mine, Lead, SD. Ultrasonic velocity measurements were also done on recovered core in the laboratory. The goal was to develop innovative technology that could enhance the safety of miners in underground mines by determining a relationship among seismic velocity, strain relief, and ultrasonic core measurements so that the state of stress in an underground pillar could be evaluated.

DESCRIPTION OF PILLAR

The pillar is 228 m (748 ft) long, 137 m (450 ft) wide, and 50 m (164 ft) high, and contains about 1.56 million m^3 (2 million yd^3) of rock at a depth of 2,260 m (7415 ft). It is composed of intensely folded Precambrian quartzites, schists, and phyllites found primarily in two formations, the Poorman and the Homestake. Poorman rocks are gray-to-black schist containing about 10% sulfides, mostly syngenetic pyrrhotite. The Homestake Formation consists of sulfides, including pyrrhotite and arsenopyrite, along with quartz, chlorite schist, carbonates (mainly cummingtonite), and gold. Fractures in the pillar are perpendicular to the haulageway or oriented 45° to 60° with respect to the direction of the haulageway. The width of the fractures near the haulageway ranges from 1 to 10 mm (0.04 to 0.4 in).

SUMMARY OF TESTS

Strain Relief Measurements

Strain relief measurement techniques were used to quantify stress in the underground pillar and to compare stress relief to seismic and ultrasonic core velocities. These measurements represent a single point. The procedure for measuring strain relief (Girard and others, 1997) consists of —

1. Drilling a hole 152 mm (6 in) in diameter to a preselected depth beyond the blasting overbreak zone.

2. Centering an EX-size (38 mm [1.5 in]) drill hole concentrically within the 152-mm-diameter (6 in) hole.

3. Placing the borehole deformation gauge into the EX hole and noting the orientation of the gauge buttons.

4. Overcoring at least 27 mm (1.1 in) on either side of the gauge centerline using a 152-mm (6 in) bit. Strains are measured as drilling progresses past the centerline.

Two holes, 7.6 and 9 m (25 and 30 ft) long, were drilled about 65° apart and nearly horizontal (figure 1). The third hole, 5.5 m (18 ft) long, was drilled at a near-vertical orientation into the back. Because of drilling problems, such as core breaking prematurely, not all strain relief measurements were used, resulting in incomplete horizontal profiles. Therefore, 13 strain relief measurements (from all three holes) were chosen from

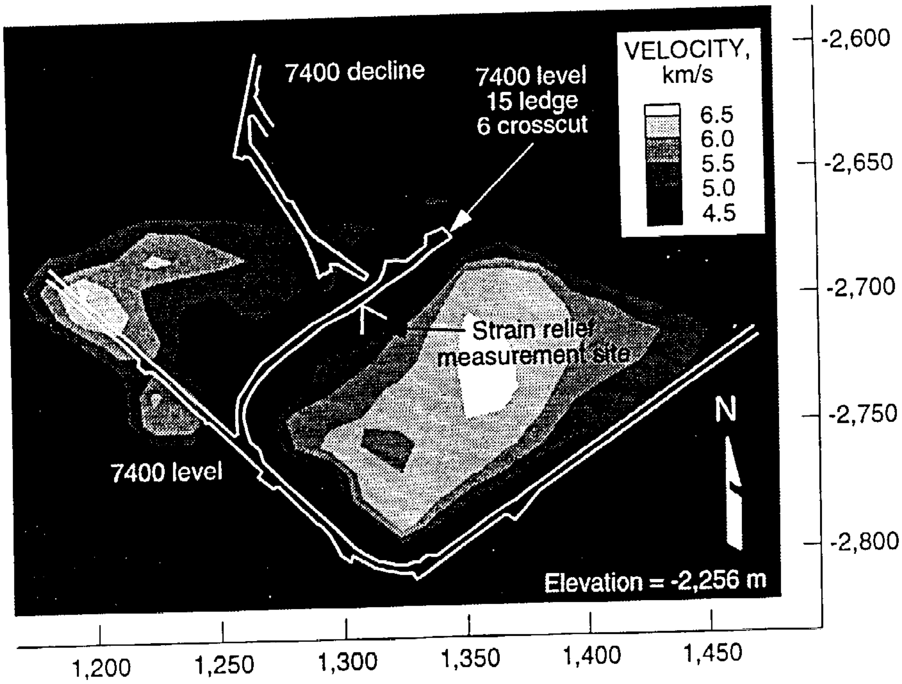

Figure 1.—Seismic tomogram, 7400 level, 1996 survey

24 attempts and averaged. The fractured rock at the drift-rib interface was thought to extend from the interface to at least 5.5 m (18 ft) into the rib. Based on this estimate, about 2 to 4 m (6.6 to 13 ft) of undisturbed rock in the pillar, as well as the fractured area in the rib, was drilled. Measured octahedral normal stress was 37 MPa (5,366 psi). Girard et al. (1997) found that a quartz unit showed higher stress than the surrounding Poorman and Homestake rocks. This quartz unit is very hard and capable of storing more stress relative to other rocks of the Poorman and Homestake formations. The abundant amounts of mica and chlorite are capable of bending and allowing a slow release of stress over time.

Ultrasonic Velocity

Thill (1982) tested sedimentary rocks and compared P-wave velocities during uniaxial compression tests. His results showed that P-wave velocities increased in samples of mudstone, shale, coarse-grained sandstone, and shaley limestone as uniaxial stress increased. Radcliffe and others (1986) also used P-wave velocities to predict the amount of stress increase. Young and Maxwell (1992) concluded that as microcracks closed in response to increased load, velocities increased. In underground pillars, cracks in rocks will also close in response to loading, with a slight increase in P-wave velocities, to a point where closure has stopped or the rock mass fails. Based on the work by Thill (1982), Radcliffe and others (1986), and Young and Maxwell (1992), an increase in seismic velocities should be expected following an increase in pressure.

Core from the strain relief measurement site (figure 1) was tested to determine P-wave velocities. Core diameter was 38 mm (1.5 in) and length was about 75 mm (3 in). The ends were ground flat and parallel. The samples (T1, T2, and T3) were dried at 60°C for 24 hours and tested. Sample T1 had variable bedding relative to the core axis; sample T2 had bedding generally 30° to the core axis; and sample T3 had bedding generally parallel to the core axis. All three samples contained mixtures of schist, quartz, cummingtonite, and sulfides. Fractures in the core were closed, and many were filled with quartz or carbonate material. The samples were tested dry in a triaxial apparatus with a confining pressure starting at 1.4 MPa (200 psi) and stablizing at 39.6 MPa (5,750 psi). Compressive loads ranged from 1.4 to 300 MPa (200 to 43,510 psi). A triaxial test was used based on Johnson's work (oral communication, 1998) on unconfined tests in Homestake core. Johnson showed an average compressive strength of 100 MPa (14,573 psi) for Homestake rocks, similar to results from our triaxial tests. The confining pressure of 39.6 MPa (5,750 psi) was chosen because it was nearly the same as the measured octahedral normal stress obtained by Girard et al. (1997). The compressive loading and corresponding velocities for core samples T1, T2, and T3 are shown in table 1.

An increase in P-wave velocities occurred in all three samples (figures 2-4) under pressures from 1.4 to 39.6 MPa (200 to 5,750 psi). In this range, crack closure was completed. In sample T1 (figure 2), P-wave velocities continued to 67.2 MPa (9,750 psi). This continued increase was probably caused by the variable bedding noted in the sample, and a good linear fit between increased P-wave velocities and increased pressure was noted. Orientation of bedding (30°-to-parallel to the core axis) in samples T2 and T3 (figures 3-4) caused P-wave velocities to decrease slightly with loading beyond 1.4 MPa (5,750 psi). These confined triaxial test results are similar to the results of unconfined compression tests measured by Johnson (1998, oral communication) from similar rocks at the Homestake Mine.

Table 1.—Ultrasonic velocity measurements

Sample	Confining pressure		Axial pressure		P-wave velocity	
	MPa	psi	MPa	psi	km/s	ft/s
T1	1.4	200	1.4	200	6.02	19,760
	39.6	5,750	39.6	5,750	6.14	20,160
	39.6	5,750	67.2	9,750	6.24	20,485
	39.6	5,750	301.6	43,750	6.27	20,585
T2	1.4	200	1.4	200	6.4	21,005
	39.6	5,750	39.6	5,750	6.6	21,645
	39.6	5,750	55.6	8,065	6.57	21,545
	39.6	5,750	165.5	24,000	6.56	21,510
T3	1.4	200	1.4	200	5.9	19,370
	39.6	5,750	39.6	5,750	6.09	19,990
	39.6	5,750	55.2	8,010	6.07	19,905
	39.6	5,750	266.2	38,605	6.09	19,995

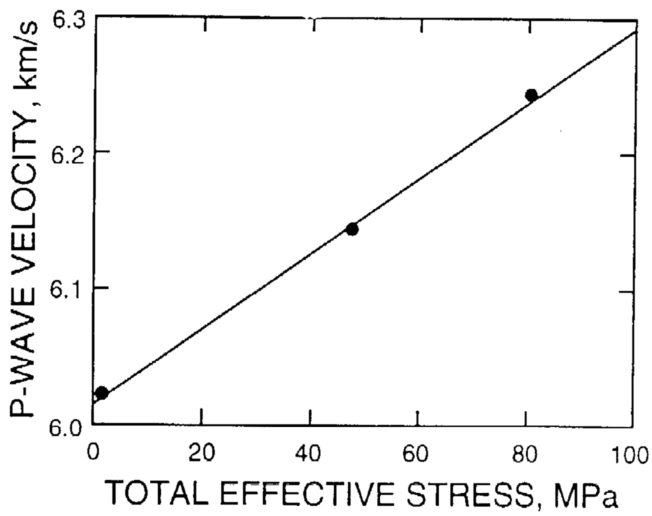

Figure 2.—Loads on sample T1.

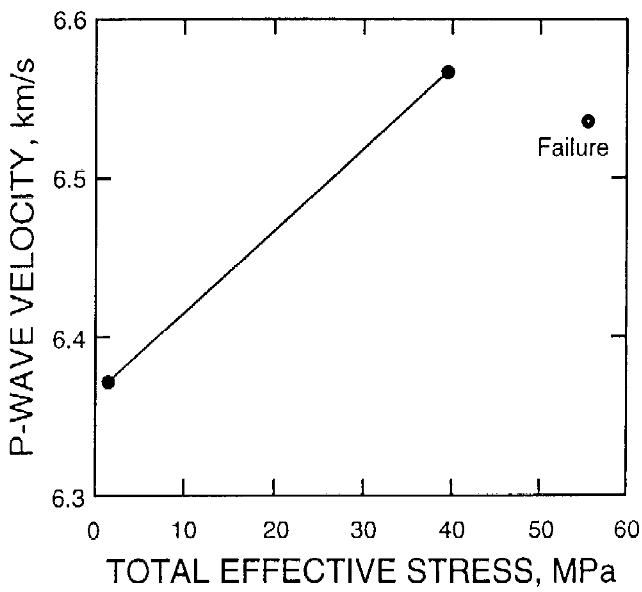

Figure 3.—Loads on sample T2.

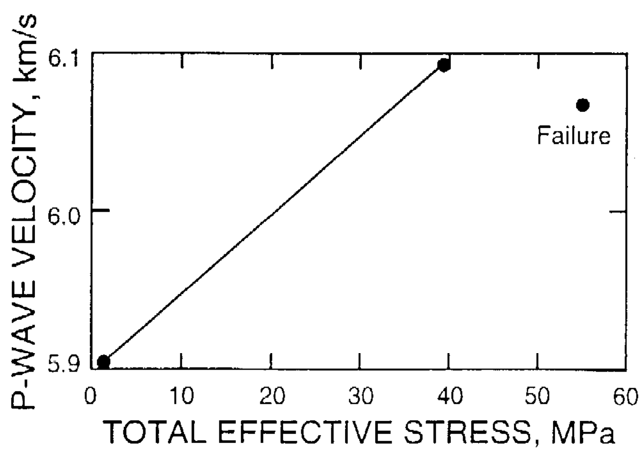

Figure 4.—Loads on sample T3.

Seismic Tomography

Seismic tomography, as used in this study, is a noninvasive geophysical technique in which seismic waves are used to penetrate a rock mass and, based on apparent velocities, infer stress gradient contours (tomograms). The technique is based on the fact that highly stressed rock will transmit relatively higher P-wave velocities than rock under less stress, as is discussed in Scott and others (1996, 1997), Scott and

Williams (1997), Friedel and others (1995a, 1995b, 1997), and Jackson and others (1995).

The technique used here requires striking a source location with a sledgehammer and a trigger connected to a seismograph and then recording arrivals of the first seismic waves at all locations where receivers (geophones) have been installed. Geophones are mounted to a rib using rock bolt plates that have been drilled, tapped, and surveyed using the mine's coordinate system. Each geophone is attached to a cable that is connected to the seismograph, and a two-pair shielded cable is used for communication and as a trigger for the seismograph. A signal-stacking seismograph is used to record P-wave arrivals, and all seismic data are transferred from the seismograph to a personal computer. The travel times (first arrivals of the seismic wave) are visually identified from the seismic records. For each seismic record, all receiver and source locations (x, y, and z), along with travel times, are recorded on a spreadsheet. The spreadsheet allows analysis of the data and saving as a text file, which can be input into a tomographic software program for reconstruction. Finally, contouring software is used to smooth the tomograms and add text and mine opening information for final presentation and interpretation.

A frequency distribution of seismic velocity projections is summarized in figure 5, and apparent velocities were reconstructed as a tomogram (figure 1). Reconstruction of seismic velocities is discussed in detail by Friedel and others (1995a, 1995b). The average P-wave velocity of 5.2 km/s (17,060 ft/s) was determined from 3,166 ray paths. The standard deviation was 1.02 km/s (3,347 ft/s) and the standard error (average velocity divided by the square root of the number of ray paths) was 0.092 km/s (302 ft/s), assuming a normal distribution. On the basis of ultrasonic tests of the core, global constraints were used in the seismic tomogram reconstruction. A low of 4.25 km/s (13,944 ft/s) and a high of 6.6 km/s (21,654 ft/s) were selected.

The area from which the strain relief measurements were collected (figure 1) corresponds to areas of low P-wave velocities (4.5 km/s [13,944 ft/s]) and is similar to the area outlining the 7400-level drift. The fractured rock surrounding the drift has low velocities because of attenuation of the seismic waves. The higher velocities (6.5 km/s [21,654 ft/s]) are believed to show areas of high stress (figure 1) (1350 to 1375 E and 2700 and 2750 N), or correspond to rock that is very hard (i.e., quartz). The closing of cracks in the pillar because of increased load would result in higher velocities.

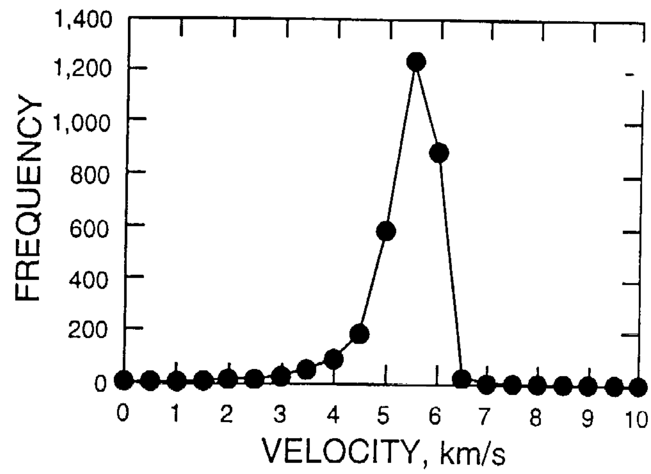

Figure 5.—Frequency distribution of seismic velocity projections, 1996 survey.

velocities. The most interesting part of the tomogram (figure 1) is two areas where the stress gradient is very steep (1340 E and 2695 N, and 1320 E and 2795 N). The distance from areas where velocities are low (4.5 km/s [13,944 ft/s]) to areas showing higher velocities (6.0 km/s [19,685 ft/s]) is about 4.6 m (15 ft). This distance is relatively short to contain a 75% increase in velocity.

CONCLUSIONS

Ultrasonic velocity core tests are a valuable tool for setting global constraints for inferring seismic velocities. Loading on three core samples (T1, T2, and T3) showed an initial increase in velocity for each sample, a result that Thill (1982) identified as being the result of crack closure in soft rocks. Velocities in the core samples averaged 6.3 km/s (20,669 ft/s) at pressures of from 1.4 to 39.6 MPa (200 to 5,750 psi) whereas P-wave velocities along the skin of mined-out openings averaged 4.5 km/s (14,764 ft/s), a 29% difference. Lower velocities in the survey measurements should be expected because of large open cracks in the pillar that were not present in the smaller core samples. An increase in core velocity from 1.4 to 39.6 MPa (200 to 5,750 psi) confirmed crack closure, as noted by Thill (1982), Radcliffe and others (1986), and Young and Maxwell (1992). Because the increased pressure in samples T2 and T3 beyond 39.6 MPa (5,750 psi) yielded no increase in velocity, future tests should be done in increments of 0.7 MPa (100 psi), starting witl 1.4 MPa (200 psi) up to about 39.6 MPa (5,750 psi). Measured overcore strain relief values of 37 MPa (5,366 psi) (Girard et al. 1997) compare to seismic velocities of about 5.2 km/s (17,060 ft/s) and ultrasonic core velocities of 6.3 km/s (20,669 ft/s). These results are encouraging as attempts are made to determine a relationship among measurements of actual seismic velocities and overcore strain relief in a rock mass and ultrasonic velocities in core.

Based on results from these studies, the skin of the drift has a seismic velocity of about 4.5 km/s (14,764 ft/s) and an in situ stress of 37 MPa (5,366 psi). Rocks in the pillar fail at 125.6 to more than 262 MPa (18,250 to 38,000 psi). The rocks near the center and upper part of the tomogram (higher velocities) are either more competent (i.e., quartz-dominated) and less fractured, or have closed fractures resulting from increased loading. These pillar rocks have the capability of withstanding an order of magnitude more stress than they currently sustain.

The combination and comparison of laboratory tests to determine core velocity, along with in situ strain relief measurements and seismic velocity studies, are useful for evaluating the state of stress in an underground pillar.

ACKNOWLEDGMENTS

The authors wish to thank Mike Friedel of the U.S. Geological Survey, who assisted in collecting and analyzing the seismic tomography data, and Jeff Johnson of the Spokane Research Laboratory, who provided expertise in interpreting the ultrasonic velocity measurements.

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